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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

TECHNICAL NOTE

No. 1088

INFLUENCE OF LARGE AMOUNTS OF WING SWEEP

ON STABILITY AND CONTROL PROBLEMS

OF AIRCRAFT

By Hartley A. Soulé

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SUMMARY

The use of large amounts of sweep has been suggested
in this country and in Germany as a means of avoiding
some of the drag increase and stability and control
difficulties encountered in high-speed flight with con-
ventional straight-wing airplanes. Experience with sweep
in tailless airplanes and studies made since this sugges-
tion has been made have indicated that the use of a large
amount of sweep will, in itself, introduce stability
and control problems of sufficient magnitude and com-
plexity to require considerable research, particularly
for flight at high angles of attack. The paper discusses
these problems and, although no proved solutions are
given, in some cases promising lines for further investi-
gation are presented.

INTRODUCTION

Early in World War II airplane speeds of the order
of 0.75 to 0.85 of the speed of sound were attained.
Because of a tendency of the airplanes to go into uncon-
trolled dives at these speeds, they have never been
exceeded although some of the airplanes operating at the
end of the war, so far as thrust and drag were concerned,
were capable of higher speeds. The instability is a
result of the radical changes in the flow over wings of
the airplane configurations in general use, which occur
at high speeds because the air is compressible. It has
been evident for some time that, if airplane speeds
are to be further increased, means will have to be
developed for preventing the occurrence of these radical
flow changes or, at least, for increasing the speed at

which they occur. To date the use of large amounts of
sweep in the wing plan form is the most promising means
for dealing with these flow changes.

Whereas sweep offers promise of improving condi-
tions at speeds above those reached at present, previous
experience with swept plan forms has indicated that large
amounts of sweep may adversely affect the stability and
control in the low speed range. It is the primary pur-
pose of the present paper to discuss the effect of large
amounts of wing sweep on the problem of designing for
stability and control at subcritical speeds.

SYMBOLS

C_L lift coefficient

C_D drag coefficient

$C_{L_{max}}$ maximum lift coefficient

C_m pitching-moment coefficient

C_Y lateral-force coefficient

C_n yawing-moment coefficient

C_l rolling-moment coefficient

C_{l_ψ} variation of rolling-moment coefficient with
          angle of yaw in degrees $\left(\dfrac{\partial C_l}{\partial \psi}\right)$

C_{n_ψ} variation of yawing-moment coefficient with angle
          of yaw in degrees $\left(\dfrac{\partial C_n}{\partial \psi}\right)$

$C_{l_{\delta_a}}$ variation of rolling-moment coefficient with
          aileron deflection in degrees $\left(\dfrac{\partial C_l}{\partial \delta_a}\right)$

C_{l_p} variation of rolling-moment coefficient with
          angular velocity in terms of $pb/2V$

REASON FOR USING PLAN FORM WITH LARGE AMOUNTS OF SWEEP

It is here proposed to review briefly the reason ... and use of sweep in the plan forms ... before proceeding with the ... stability and control problems. For some ... stability problems were encountered ... it was found that when the ... wing sections approached the ... Mach number of from 0.75 to 0.85 ... section, a radical change ... occurred. At this speed, ... break speed, the angle of attack ... wings shifted to a more ... slope of the lift curve was reduced, ... increased. As a result of the shift of ... the reduction of slope of the lift ... when it passes force break speed ... angle of attack suddenly increased in ... support the weight. Unfortunately the change

of zero-lift angle and the reduction of lift-curve slope
also cause a reduction of the downwash at the tail, which
in turn produces an upload on the tail giving a nose-
down pitching moment and tends to lower the angle of
attack for trim. In addition, the reduction of lift-
curve slope means a reduction of the variation of angle
of downwash with angle of attack, which increases the
longitudinal stability of the airplane about the new
reduced trim angle of attack. The combination of these
effects calls for a relatively large up-elevator deflec-
tion for maintenance of steady flight. The forces
required for this deflection are generally beyond the
capabilities of the pilot, hence the general report of a
"frozen" elevator control and a "tucking under" tendency
of airplanes at high speeds. These phenomena, it has
been found since the end of the war, were encountered
by pilots of all the warring nations.

The use of sweep is based on the concept that, for
a wing with parallel leading and trailing edges, the lift -
that is, the pressures that result in lift - is generated
only by the velocity component perpendicular to the
leading and trailing edges. Hence, when such a wing is
yawed or swept, the velocity normal to the leading edge
is reduced in proportion to the cosine of the yaw angle
relative to the resultant velocity. This concept is
utilized in most potential-flow theory. Early in the
war, it has been recently discovered, Betz in Germany
suggested the use of sweep for increasing the wing
critical speed. In this country Jones in 1944 (refer-
ence 1) independently made a similar suggestion. The
concept on which these suggestions are based is not
strictly applicable to tapered and finite-span wings;
however, experiments in both countries have been made
which show that, while the full gain indicated by the
simple theory is not attained, a swept wing does offer
considerable advantage over an unswept wing.

On the basis of the same concept it can be shown
that the pressure drag of a wing is also reduced by
sweep. At supersonic speeds the pressure drag constitutes
an important part of the total wing drag. Even if the
instability of airplanes at high speeds was to be
eliminated by other means, it is very probable that
sweep still would be considered for supersonic-speed
airplanes because of its effect on wing drag.

In order to give an idea of the amount of sweep
necessary to obtain a reasonable increase of critical
speed, figure 1 has been prepared presenting critical
Mach number as a function of angle of sweep. The fig-
ure is based on the elementary assumption that the
critical Mach number or speed at any angle of sweep
equals the critical speed for zero sweep divided by the
cosine of the angle of sweep. A value of $M = 0.8$ has
been chosen to represent the critical speed for the zero
sweep condition. Experiments with three-dimensional
wings have shown that, because the original concept is
not applicable at the wing root and tips, the actual
gain in critical speed resulting from sweep is of the
order of one-half that shown by figure 1. The figure
shows that very little is to be gained in critical speed
with angles of sweep of less than $30°$. Angles of sweep
of $40°$ to $45°$ appear necessary in order to obtain an
appreciable gain in critical speeds, particularly since
the actual gain may be only half that shown by the
figure.

PROPORTIONS OF SWEPT WINGS

For wing plan forms there are three basic dimensional
parameters: aspect ratio, taper, and sweep. If these are
taken as independent parameters, it is possible to
derive a systematic series of wing plan forms covering all
possible combinations that might be considered for high-
speed aircraft. Some of the swept-back wings of this
series are illustrated in figure 2. In practice the
three parameters are related by strength requirements.
From simply an inspection of the figure it is immediately
evident that high aspect ratios and large angles of
sweep are probably not compatible structurally.

In order to avoid a waste of time on aerodynamic
studies of structurally impracticable configurations,
it appears desirable to determine structural limitations
more closely than can be done by visual inspection.
The ratio, wing length divided by wing root thickness,
is a generally accepted criterion of structural efficiency.
At the present time the average value for this ratio falls
between 30 and 35. In at least one case a value of 50
has been obtained. A larger value may be obtained at
some later date, but 50 probably can be taken as representa-
tive of practical structures in the near future.

On the basis of the ratio of wing length to root
thickness of 50, the wing with aspect ratio 8 and taper
ratio 0.5 would have to have a root section with a ratio
of thickness to chord of 0.12. With sweep the root
section would have to be relatively thicker because, for
the same aspect ratio, the panel length is increased and
the chord is decreased, as illustrated in figure 2.
As an increase in the ratio of section thickness to
chord decreases the critical Mach number, it is evident
that, if the thickness is increased as the wing is swept,
some of the advantages of sweep will be lost. Further-
more, theory indicates that at the root the alleviating
effect of sweep on drag is not obtained, which is
another reason for keeping the root thickness small.
Because of these considerations, it is probable that for
high-speed aircraft the ratio of section thickness to
chord will be held to 0.10 or less. If 0.10 is taken
as a limiting value for this ratio, no wings of aspect
ratio 8 and taper ratio 0.5 are structurally practicable
for high-speed aircraft. With an aspect ratio of 2 and
a taper ratio of 0.5, structural considerations will
limit the angle of sweep to about 55°. For the pointed
wing plan forms the limiting sweep for aspect ratio 8
is 25° and for aspect ratio 2 is 65°. For the present,
therefore, it is apparent that large amounts of sweep
imply low aspect ratios and some of the stability
problems referred to as relating to large angles of
sweep actually result, at least in part, from the
accompanying low aspect ratios.

REPRESENTATIVE DATA ON THE AERODYNAMIC CHARACTERISTICS

OF SWEPT-BACK WINGS

When the use of sweep for high-speed airplanes was
suggested in this country, German data on the subject
were not available. For purposes of evaluation of the
low-speed stability and control problems the NACA made
tests at low Reynolds numbers of a series of swept wings
of taper ratio 1. These tests are reported in detail
in reference 2. As a later inspection of German test
data showed that the information obtained is fairly
representative and as the information of reference 2
has been used as a basis for some of the later discussion,
a part of the data has been reproduced in the present

paper so that some of the detail characteristics which
could not be otherwise covered might be inspected.

Figure 3 gives the dimensional characteristics of
the wings tested. The wing section was an NACA 23012.
The span and the chord of the wing measured perpendicular
to the leading edge were the same for all angles of
sweepback. The dihedral was zero and the wing tips
were cut off parallel to the air flow. Semispan split
flaps and semispan ailerons and spoilers were tested
on the wings. The Reynolds numbers for the tests varied
from about 1,000,000 to 2,000,000, depending on the angle
of sweep.

The lift, drag, and pitching-moment coefficients
for the wings without flaps are shown in figure 4 as a
function of angle of attack. With the unswept wing
the pitching-moment-coefficient curve is straight up
to the stall and then bends down, giving a diving moment.
This type of curve is normal for straight wings. As was
anticipated from past experience with tailless airplanes,
for large angles of sweep the pitching-moment curve turns
up at the stall, giving a stalling moment that tends to
hold the wing above the stalling angle. What was not
anticipated was the increase of the negative slope of
the curve of pitching-moment coefficient which occurs
below the stall with angles of sweep of 45° and 60°.
Although the practical importance of this negative slope
has not been established, it is a matter of some concern,
particularly for wings with 60° sweep for which the
change of slope occurs at angles of attack corresponding
to high-speed flight. The reason for the concern is
that a change of slope in the pitching-moment-coefficient
curve represents an increase in longitudinal stability.
As will be recalled, an increase of longitudinal stability
is one of the factors contributing to the present high-
speed stability troubles with straight-wing airplanes.
With straight-wing airplanes, however, the change of
slope is much greater than is illustrated in figure 4.

With regard to lift coefficient, the main effect
of sweep is to reduce the variation of lift with angle
of attack. Part of the reduction may be attributed
directly to the reduction in aspect ratio. An addi-
tional point to be noted is that for the wings with 45°
and 60° sweepback (fig. 4) the lift curves have a point
of inflection where the slope is noticeably increased.

The change of slope of the lift and pitching-moment curves
for a given amount of sweepback occurs at the same angle
of attack indicating that, through some unknown mechanism
of the flow, the variation of lift of the wing tips with
angle of attack suddenly increases at a critical angle.
Tuft studies show that this change is accompanied by a
slight ruffling of the tufts near the leading edge about
40 percent of the semispan from the root. The shape of
both the lift and pitching-moment curves may be affected
by erecting a small barrier to spanwise flow in the
boundary layer at this point. The effect of sweep on
the maximum lift coefficient and on the angle of attack
at which it occurs will be discussed later. The drag
curves are of interest only as indicating the large
magnitude of the drag for the swept wings at high lift
coefficients.

Figure 5 shows the variation of lateral-force,
yawing-moment, and rolling-moment coefficients with angle
of sideslip for the same series of wings at an angle of
attack of approximately 11°. It shows primarily that the
functions, with the exception of those for the wing
with 60° sweep for C_Y and C_n, vary in an orderly
manner with yaw and sweep. The reversed slopes, for the
60° swept wing, of the lateral-force and yawing-moment
curves are representative of the erratic conditions that
exist with all the swept wings at some angles of attack.
Apparently these conditions are associated with the flow
change previously mentioned in connection with the
lift and pitching-moment curves and with the stalling of
the wing tips.

Figure 6 is representative of the effect of
installing a half-span split flap with a 60° deflection
on the lift, drag, and pitching-moment coefficients of
a swept-back wing. The effects on lift are similar to
those for a straight wing, although the increments of
lift caused by the flap are less and the wing with flaps
stalls at a lower angle of attack than the wing without
flaps. The diving moment normally resulting from a
flap deflection on a straight wing is reduced by virtue
of the fact that the center of lift for the flap is ahead
of the center of lift for the plain wing. The flap adds
an almost constant increment of drag throughout the angle-
of-attack range tested. It is of interest to note that
the wing with flaps has a lower drag at the stall than
the wing without flaps.

LONGITUDINAL STABILITY AND CONTROL

Practically all of the following discussion is based on the test data of reference 2 or of similar investigations made at relatively low Reynolds numbers. As a number of the characteristics treated, particularly those relating to conditions at high angles of attack, may be critically dependent on boundary-layer conditions and, hence, on the Reynolds number of the tests, it should be appreciated that the points made can in no way be considered final. They are advanced at this time simply as the best available and as an argument for the need for studies at large Reynolds numbers.

Minimum Speed and Landing

The effect of sweepback on airplane minimum speeds is indicated in figure 7, which gives the variation of the maximum lift coefficient and the variation of the angle of attack for maximum lift coefficient with angle of sweepback for the plain wings and for the wings with half-span split flaps. So far as the plain wings are concerned, a relatively small change of maximum lift with sweepback is shown. The values of maximum lift coefficient for the wings without flaps are actually greater at small angles of sweep than for the straight wings. With flaps, however, the greatest value of maximum lift is attained with the straight wing. The effect of the flaps on maximum lift decreases with sweep, and for an angle of sweep of 60° the gain in lift resulting from the flaps is negligible. At angles of attack below the stall, however, there is still an appreciable change of lift due to flap deflection at a given angle of attack.

The angle of attack for maximum lift is important because of its influence on landing-gear design and vision at landing. For the plain wing, the angle of attack for maximum lift is approximately doubled when the angle of sweep is increased from 0° to 60°. Flaps decrease the angle of attack for maximum lift by an amount increasing with angle of sweep. Even with flaps, however, the angle of attack for maximum lift is considered excessive for large angles of sweep because the stowage of even a landing gear of normal length in an airplane with thin wings is difficult. Fortunately airplanes designed for very high speeds will have so much available thrust that take-offs need not be made at angles

of attack near maximum lift. It may be possible, there-
fore, to proportion the landing gear for take-off and
to allow the airplane to touch tail first and rock over
on the gear at landing.

The high drag at maximum lift for the swept wings
has been previously mentioned. The significance of the
high drag is indicated by figure 8 in which is plotted
the variation of glide angle at maximum lift with angle
of sweepback. In this particular case the low Reynolds
number of the tests affects the quantitative values and
some revision is expected when full-scale data become
available. Some such variation of glide angle is to be
expected, however, as the induced drag will normally
increase with the decrease in aspect ratio accompanying
sweep. The importance of the 30° glide angle for the
60° swept wing without flaps will be appreciated if it
is recalled that the vertical velocity equals the velocity
along the flight path times the sine of the glide angle.
As the sine of 30° is 0.5, the vertical velocity will be
about one-half the approach speed, or about 75 feet per
second when the minimum speed is 100 miles per hour.
The flight study reported in reference 3 has indicated
that, when the vertical velocity exceeds about 25 feet
per second, the piloting technique of judging the point
to start the landing flare and of executing the flare so
that the vertical velocity will be reduced to a reasonable
value for contact becomes extremely difficult.

Rather surprisingly, flaps for the larger angles
of sweep decrease the glide angle. This decrease appears
to be associated with the lower angles of attack for
maximum lift with flaps down. Figure 6 has shown that
the drag increase resulting from the flap deflection is
more or less constant as the angle of attack is varied.

It is appreciated that figure 8 does not give a
complete picture of the landing problem. In actual
landings, pilots make the landing approach at speeds
in excess of the minimum speed so that they will have
energy available to flatten out the flight path just
prior to contact. The glide angle at maximum lift,
however, is a rough measure of the margin of speed
needed for the approach glide and the indications are
that the landing-approach speed will have to be much
higher for wings with large amounts of sweep than for
straight wings, even if equal landing speeds are assumed.

Another means used for reducing vertical velocities at
landings is the application of power in the approach.
The problem of carrying enough fuel for reasonable
duration and range of flight is admittedly difficult for
high-speed airplanes, but the provision of reserve fuel
for landing appears to be essential.

Longitudinal Stability

In figure 4 it was noted that, for the wing con-
figurations illustrated, sweep caused an unstable variation
of the wing pitching-moment-coefficient curve at stall.
Inspection of other data has shown that this result
should be attributed to the particular configurations
tested. Other data on the pitching moment of swept
wings are given in figure 9 where pitching-moment coef-
ficient is plotted as a function of lift coefficient for
other representative swept-wing configurations. It is
shown that for certain combinations of taper and aspect
ratio an unstable variation of pitching moment at the
stall may be obtained with large amounts of sweepback.
On the other hand, the lower right-hand curve shows the
interesting fact that with some configurations there may
be a continuously increasing stable variation of the
pitching-moment coefficient with lift coefficient.

Some consideration of what is wanted in the way
of a pitching-moment-coefficient curve is desirable at
this point. Perhaps it is best to consider the curve
for the complete airplane first. The most important
point is that for plots of the type given in figure 9
there should be no large amounts of curvature of the
pitching-moment curves. Curvature signifies an aero-
dynamic center or "neutral point" variation with speed
which makes it difficult to obtain stability throughout
the complete speed range without obtaining excessive
stability in certain speed ranges. Extreme upward
curvature at the stall is particularly dangerous because
it tends to promote inadvertent stalling. For tailless
airplanes the remarks for the complete airplane apply
directly to the wing. For airplanes with tails the wing
characteristics may be masked because of the influence
of the tail on the pitching moments. Even for airplanes
with tails, however, it is considered advisable as a
first approximation to choose a wing configuration
having relatively good pitching-moment characteristics.

Data of the type given in figure 9 have been inspected
for more than 40 wing configurations with various amounts
of sweepback. The results of this inspection have been
summarized in figure 10. Although aspect ratio, sweep,
and taper were considered as possible parameters, the
figure shows only aspect ratio and sweepback as variables
because taper turned out to be only of secondary importance.
The curve shown is for the approximate variation of aspect
ratio and angle of sweepback for which the pitching-
moment curve against lift is a straight line. In the
upper right-hand portion of the figure the moment curve
turns up with increasing lift whereas in the lower left-
hand portion it turns down. The greater the distance
from the curve shown the greater is the curvature of the
pitching-moment curves.

Apparently with different aspect ratios, it is
possible to get a pitching-moment-coefficient curve with
either upward or downward curvature with any angle of
sweepback. If upward curvature, which may be dangerous,
is to be avoided, the aspect ratios will have to be
reduced when the angle of sweepback is increased. This
conclusion is similar to the conclusions previously
drawn from consideration of structural requirements.

Because the unstable pitching moments encountered
with swept-back wings of high aspect ratios are the
result of wing-tip stalling, considerable attention is
being given to means for improving the lift characteristics
of the tip portions. There is an additional interest in
leading-edge lift-increasing devices because, for airplanes
designed for very high speeds, sections with sharp leading
edges, which have poor lift characteristics, may be
required regardless of sweep. These devices take three
general forms as illustrated in figure 11 - slots, nose
flaps, and drooped leading edges. All these devices can
be expected to give some increase in section lift charac-
teristics, with slots having the greatest effect. Slots
may be either fixed or movable. Just how effective the
devices will be on a swept leading edge has not been
definitely established. German information is confusing -
proponents of leading-edge flaps think slots will not
work and vice-versa. In tests made by the NACA with
slots on a wing swept back 60°, no gain in lift was
obtained. The teets, while not conclusive, at least
indicated that slot proportions will be more critical on
swept than on straight wings.

The effect of the horizontal tail on the longitudinal
stability depends on the downwash at the tail location.
Very little information exists on the downwash field
behind swept wings. From the fact that the downwash
behind a straight wing increases with a decrease in
aspect ratio, it would be deduced that with large amounts
of sweep the horizontal tail would contribute little
to the longitudinal stability and hence the interest in
the tailless configuration for airplanes designed for
very high speeds.

A preliminary investigation has been made to deter-
mine the downwash field behind swept-back wings. Fig-
ure 12 shows the wing and tail arrangement which was
tested, and figure 13 shows the variation of the angle
of downwash with the angle of attack. In the investi-
gation the average downwash over the tail was determined
by finding the tail setting at which the contribution of
the tail to the pitching moment was zero. Two tail
heights and two tail lengths were studied. In figure 13,
which gives the results, the lift curve for the wing is
also presented. The figure shows that for the lower lift
coefficients the downwash is approximately a linear func-
tion of lift coefficient. The slopes in this range, as a
function of angle of attack, vary from 0.55 with the tail
low and forward to 0.38 with the tail aft and high.
Vertical movement of the tail has a greater effect on
downwash than fore-and-aft movement. In no case is the
rate of change of downwash much greater than the value
of 0.5 generally considered representative of straight
wings of normal aspect ratios.

At lift coefficients above that where flow changes
occur on the wing, the tail location has a pronounced
effect on the integrated downwash at the tail. Of
particular interest is the curve for the short, high
tail location. The increased slope shown for the high-
lift-coefficient range signifies a decrease in the con-
tribution of the tail to longitudinal stability. In
this case the combination of wing and tail is actually
less stable than the wing alone. The other curves indi-
cate an increase in the contribution of the tail to sta-
bility at high lifts. It is concluded that tail location
is as important as wing configuration for the attainment
of uniform longitudinal-stability characteristics through-
out the speed range and that the tail may, depending on
its location, either increase or decrease the stability
in the vicinity of stall.

LATERAL STABILITY AND CONTROL

Dihedral Effect

With regard to lateral stability and control, the influence of sweep on the rolling moment due to sideslip or the "effective dihedral" appears to be of primary importance. Figure 14 shows the variation of the rolling-moment coefficient with sideslip C_{l_ψ} as a function of

lift coefficient for several angles of sweepback. The information was obtained from the tests for which representative data were illustrated in figure 5. The increasing slope of the curves with sweepback is apparent. Of particular interest is the fact that there is a maximum value obtained regardless of sweepback. This value is equivalent for the wings tested to over $20°$ of geometric dihedral on a straight wing. Higher-scale tests will be needed to establish the value more definitely. The reason for the limiting value is not known but it is probably connected with boundary-layer conditions and stalling of the wing tips. As the parameter C_{l_ψ}

increases with lift coefficient, the stability problems of sweep are generally problems of flight at high angles of attack.

Figure 15 is a plot of the slopes of the straight portions of the curves of figure 14 as a function of angle of sweepback. The theoretical curve takes into account the velocity and angle-of-attack changes that occur over the wing section with yaw. (See reference 2.) It is of interest that the values can be predicted with reasonable accuracy.

Lateral Stability

The significance of the large variation of rolling-moment coefficient with angle of sideslip, insofar as lateral stability is concerned, is shown by figure 16. This chart shows the boundary between associated values of the variation of rolling-moment coefficient with sideslip C_{l_ψ} and the variation of yawing-moment coefficient with sideslip C_{n_ψ} that give so-called "dutch roll" instability and stability. The values are for

representative airplanes with two values of wing loading
and two values of angle of sweepback. For the basic
airplane the sweep was zero. The 40°-sweep case was
obtained by considering each half of the wing swept
back 40° with no change of panel length, and hence the
span and aspect ratio for the swept-wing case was lower
than for the straight wing. The span is a parameter of
the stability equations and the reduction with sweep
was taken into account in the preparation of the figure.
The figure shows that with 40° sweep more directional
stability is required than for the straight wing. For
the value of wing loading of 104 at the ground, condi-
tions are particularly bad, the minimum value of C_{n_ψ}

required for stability being at least twice that for a
conventional airplane. As the coefficient C_{n_ψ} varies

inversely with the wing span, it should be appreciated
that a given vertical tail will give a value of the coef-
ficient about 1.4 times greater for a 40° swept wing than
for the comparable straight wing. Since the increase in
the value of C_{n_ψ} due to the reduced wing span is less

than that required for satisfactory stability, larger
vertical tails are apparently indicated for swept-wing
airplanes. For the airplane investigated an increase of
fin area of about 40 percent appears indicated. An
increase of tail length both for lateral and longitudinal
stability would appear desirable if the weight-balance
problems could be worked out. One unfortunate feature about
increasing vertical-tail size is that with the tail on top
of the fuselage the fin itself contributes to the rolling
moment due to yaw. If care is not taken, the designer
can get into a vicious circle where increasing fin size
because of its effect on rolling moment demands a further
increase and so on. The other means of avoiding lateral
instability with swept-back wings is to use negative
geometric dihedral by bending the wings down at the tips,
either full or partial span. There is some concern as to
the effect of the negative dihedral at low lift coeffi-
cients, although experience indicates that small values
of negative dihedral have no detrimental effect except
that the ailerons must be used to keep the wings laterally
level.

The contribution of the fin to the rolling moment
due to yaw decreases with angle of attack because of the
lowered position of fin center of pressure. It has been
suggested, therefore, that a combination of negative

wing dihedral, large fin area, and a relatively long tail
might result in the most satisfactory configuration. If
the proportions are correctly chosen, it appears possible
to obtain a small variation of the rolling-moment coeffi-
cient due to sideslip with angle of attack or lift coef-
ficient. For practical reasons, such a combination will
probably be impossible. The negative dihedral is limited
by ground clearance and the tail length by weight-balance
considerations. The method even with compromises,
however, appears most promising at the present time.

Aileron Control

The aileron control for swept wings is a function
of the direct rolling moment of the ailerons, the damping
in roll given by the wings, and the rolling moment of the
wings due to yaw coupled with the weathercock stability
of the airplane. Some indication of the direct rolling
moment of the ailerons was obtained from the systematic
series of tests previously mentioned. The results are
summarized in figure 17 where the rolling moment for a
unit deflection of a semispan aileron is shown as a
function of angle of sweepback. The theoretical curve
is again based on the simple theory. The results show
that the direct moment due to the aileron drops off with
sweepback and that the aileron characteristics are
satisfactorily predicted by the simple theory.

Figure 18 gives data for spoilers located on the
upper surface at 0.8 chord behind the leading edge and
extended 0.05 chord. Spoiler effectiveness is reduced
with sweepback more rapidly than aileron effectiveness
and spoilers are totally ineffective for large angles of
sweepback. The reason for this ineffectiveness with
large angles of sweepback appears to be related to
boundary-layer conditions on the wing upper surface with
large amounts of sweepback. The observations have shown
that at the spoiler location the flow in the boundary
layer is nearly parallel with the spoiler and that the
boundary-layer thickness increases rapidly with angle of
attack.

The effect of sweepback on the damping moments of
a rolling wing is shown in figure 19. The same data
have been plotted against angle of attack and lift coef-
ficient. The figure shows that below the stall the
damping moments of wings are reduced by sweepback. The

decrease, however, is not so great as the decrease in aileron power. Another point of interest shown by the figure is the low damping moments for the swept-back wings at and above the stall. In contrast, the figure shows that for the straight wing for a range of angle of attack just above the stall large positive moments exist indicating autorotative tendencies.

Figure 20 shows data obtained by deflecting ailerons on the wings shown in figure 19 and recording the rolling velocities. The solid-line curves give the total aileron deflection required for a value of $pb/2V$ of 0.1. A considerably greater aileron deflection is required for the wing with an angle of sweep of 60° than for the wing with an angle of sweep of 0°. The difference, however, is not too significant because the rolling parameter $pb/2V$ does not take into account the change of rolling velocity that results from a change of span. The rolling velocity for the 60° swept wing, for example, will be approximately twice that of the wing with zero sweep for the same value of $pb/2V$. Apparently normal ailerons of the same proportions as those used on straight wings will be satisfactory for swept wings. The dashed curves of figure 20 represent the aileron deflections that were computed by procedures normally used for straight wings with a knowledge of aileron characteristics for zero rate of roll and damping moments for zero aileron deflection. The agreement with the measured values is satisfactory.

Rudder Control

Little attention has been paid up to the present time to the rudder control for high-speed airplanes. This condition is a result of the belief that because of the large rolling moments accompanying sideslip with swept wings the rudder will be an extremely powerful rolling control and its use will generally be avoided. It is not yet considered advisable to eliminate the rudder from high-speed airplanes because of possible use when taxying; rudder-locking devices may have to be provided to avoid its inadvertent use at high speeds.

Control Hinge Moments

Sweep has been proposed on the theory that the velocity component producing the normal force and

consequently affecting the major aerodynamic parameters
equals the velocity of the airplane times the cosine
of the angle of sweep. This theory apparently is valid
when applied to certain stability characteristics, as
has been discussed. In regard to control hinge moments,
therefore, it is expected that for a given size surface
sweep reduces the hinge moments. Most balances used
for straight wings can probably be satisfactorily applied
to swept wings.

SWEEPBACK VERSUS SWEEPFORWARD

Most of the data that have been presented apply to
swept-back configurations. As the arguments in favor of
sweep for high-speed airplanes apply equally well to
sweepforward, the question naturally arises as to the
consideration given this alternate configuration. A
study is being made of sweepforward but it has not
proceeded as fast as that of sweepback because of the
smaller amount of existing knowledge about it when
sweep was proposed. The differences in characteristics
are apparently as would be expected. Sweepforward tends
to inhibit wing-tip stalling but promotes wing-root
stalling. In both cases instability at high angles of
attack may occur. With sweepforward the rolling moment
due to yaw decreases with increasing lift; this condition
may be advantageous from the standpoint of lateral
stability.

POSSIBLE HIGH-SPEED EFFECTS

So far the discussion has been confined to subsonic
characteristics. The data presented were obtained at
low subsonic speeds. In the subsonic-speed range the
characteristics may be expected to vary according to
the Prandtl-Glauert rule in the same manner as they do
for a straight-wing airplane. For characteristics dependent
on the over-all flow the Mach number for the application
of established corrections, as in the case of downwash,
should be based on the general flow. For detail charac-
teristics, as aileron hinge moments for example, the
Mach number should be based on the normal component of
the local flow. Except for such details as hinge moments,

there is no proof that the corrections will apply beyond
Mach number 1 where the fuselage flow becomes supersonic.

For the transonic regime - that is, where the normal
flow is above the equivalent force break speed - practically
no data exist. As a first approximation it is assumed
that for moderate aspect ratios the problems encountered
will be similar to those encountered with straight wings
at lower speeds. For the very low aspect ratios that
occur with short-span triangular plan forms some evidence
exists that the center-of-pressure location will be
independent of Mach number indicating that, as far as
longitudinal stability is concerned, for this configura-
tion no difficulty is expected through any speed range.

According to theory for straight wings, in subsonic
flow the aerodynamic center will be at approximately
25 percent of the wing chord while in supersonic flow
it will be at 50 percent; for narrow triangular plan
forms the aerodynamic center should be at approximately
the center of area at all speeds. Swept-back plan forms
should fall between these extremes. Available test data
indicate that such is the case. In the transonic regime
the location of the aerodynamic center for straight wings
is more or less unpredictable at present. The aerodynamic
center for the transonic regime depends on the thickness
distribution with its resultant effect on the pressure
gradients behind the shock wave. Local flow separation
may result from steep gradients with a consequent change
in the load distribution. It is suspected that the center
of pressure may vary with time at the same Mach number
and angle of attack. Aileron buzz is thought to be a
manifestation of this phenomenon. While no supporting
evidence is available, it is thought that the transition
processes will be more orderly with sweep because of the
obliquity of the wave front when transition occurs and
because the flow may be wholly supersonic.

Downwash changes, which are the worst features of
the transonic regime, can be expected to be delayed with
sweep. Whether they can be avoided is a debatable
question. It is more probable that they cannot. Maybe
the magnitude of the downwash changes will be reduced.
At present, however, for airplanes with horizontal tails
the possibilities are that an increase in the longitudinal
stability will occur at some speed and this factor should
be considered in design. An adjustable stabilizer appears
to be a requisite feature of high-speed airplanes. The

other alternative is the tailless configuration which
the Germans have given a lot of attention.

The lateral-stability discussion concerning the
relation between dihedral and directional stability
applies at all speeds, as there is nothing to indicate
that the effective dihedral will change with the speed.
The directional stability, however, may increase at high
speeds because of the relatively greater contribution
of the drag.

Control hinge moments will increase with speed and
control balancing is expected to be an important problem
regardless of sweep.

Langley Memorial Aeronautical Laboratory
        National Advisory Committee for Aeronautics
                Langley Field, Va., April 16, 1946

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2. Letko, William, and Goodman, Alex: Preliminary Wind-
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        NACA TN No. 1046, 1946.

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        The Effect of High Wing Loading on Landing Technique
        and Distance, with Experimental Data for the
        B-26 Airplane. NACA ARR No. L4K07, 1945.
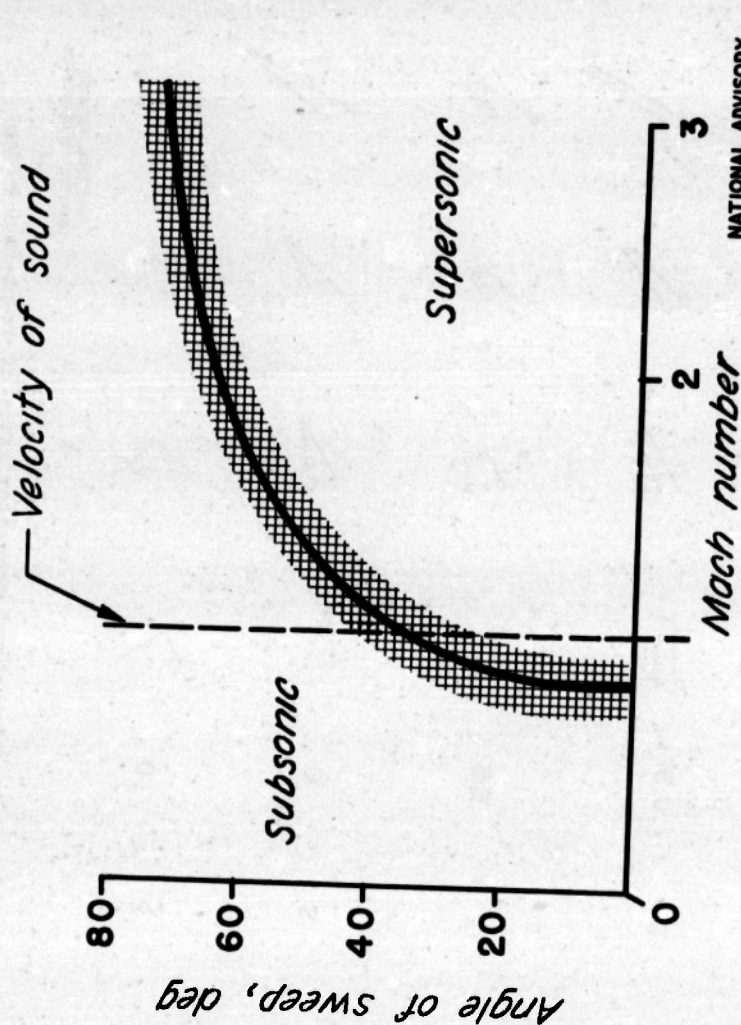
Figure 1.- Effect of angle of sweep on critical Mach number as predicted by simplified theory.

Fig. 2   NACA TN No. 1088
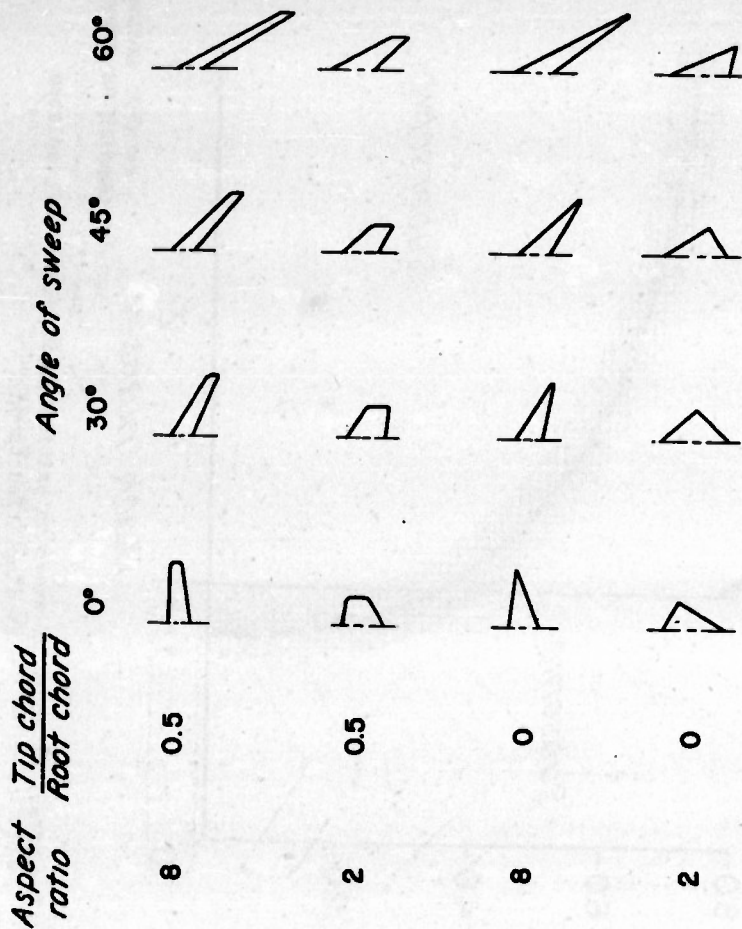
Figure 2.- Dimensional characteristics of swept-back wings.

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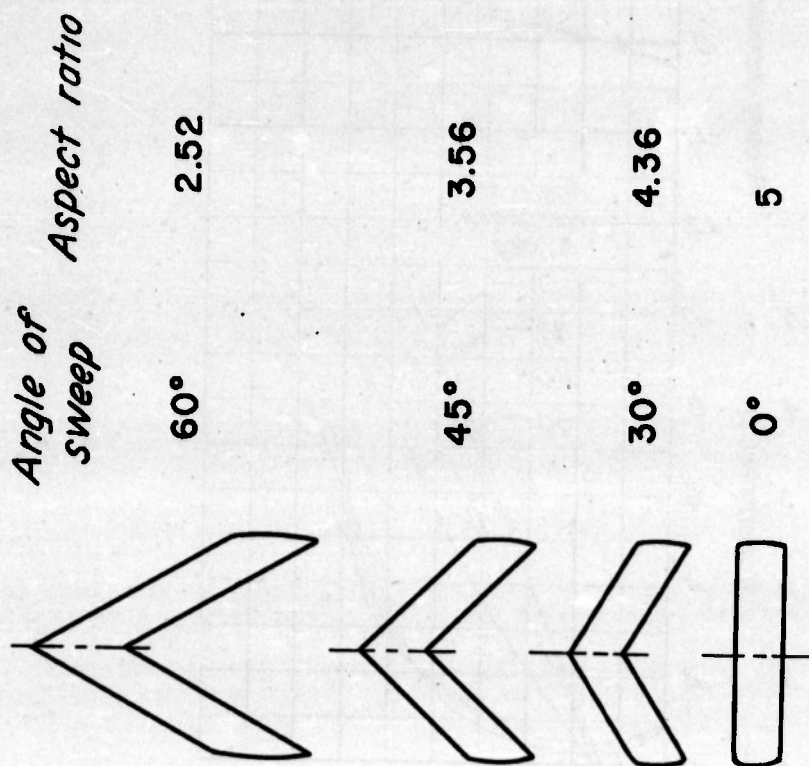
Figure 3.- Series of swept-back wings used in tests reported in reference 2.

Angle of sweep	Aspect ratio
60°	2.52
45°	3.56
30°	4.36
0°	5

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Fig. 4

NACA TN No. 1088
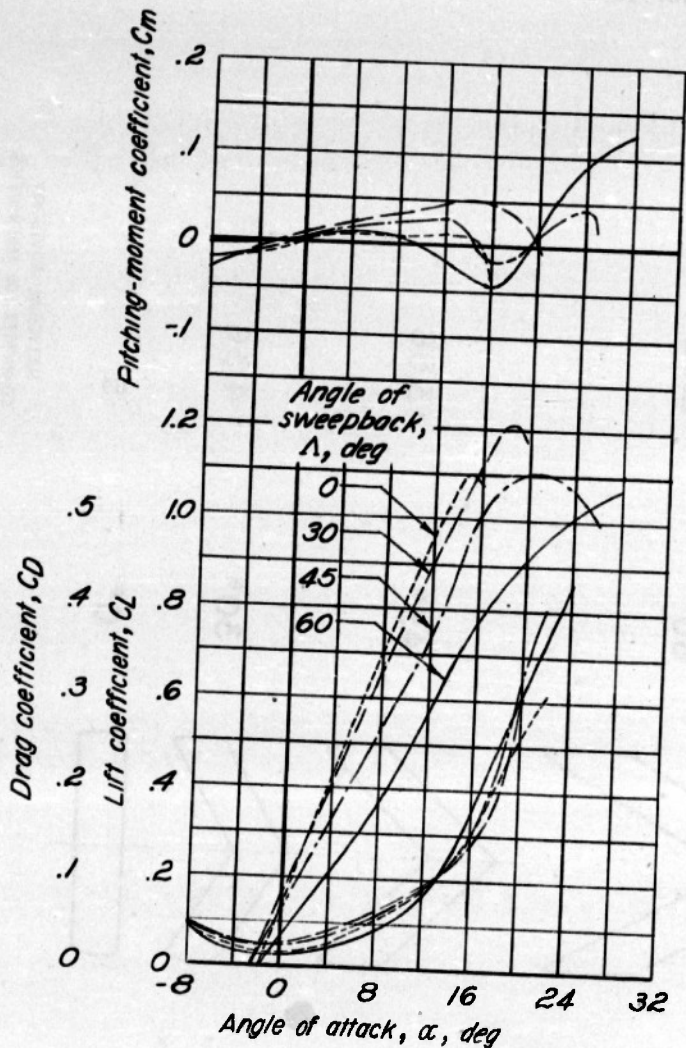
Figure 4.- Representative data from reference 2 showing the effect of sweepback on lift, drag, and pitching-moment coefficients.
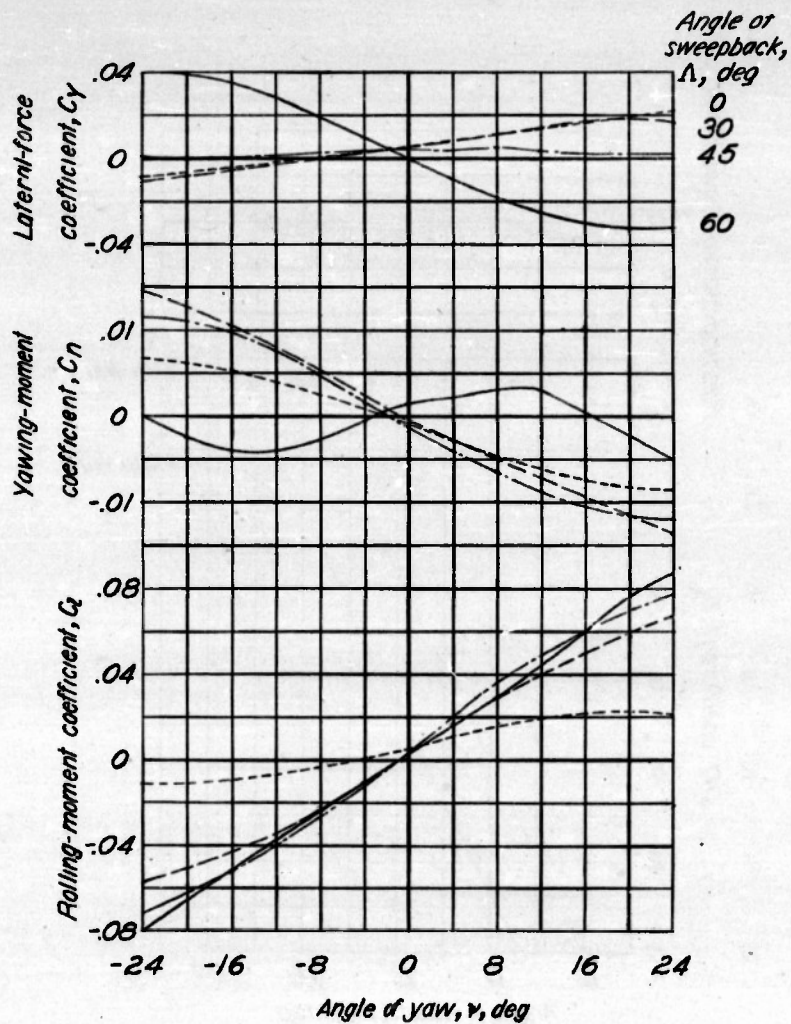
Figure 5.- Representative data from reference 2 showing the effect of sweepback on lateral-force, yawing-moment, and rolling-moment coefficients. $\alpha = 11^6$.
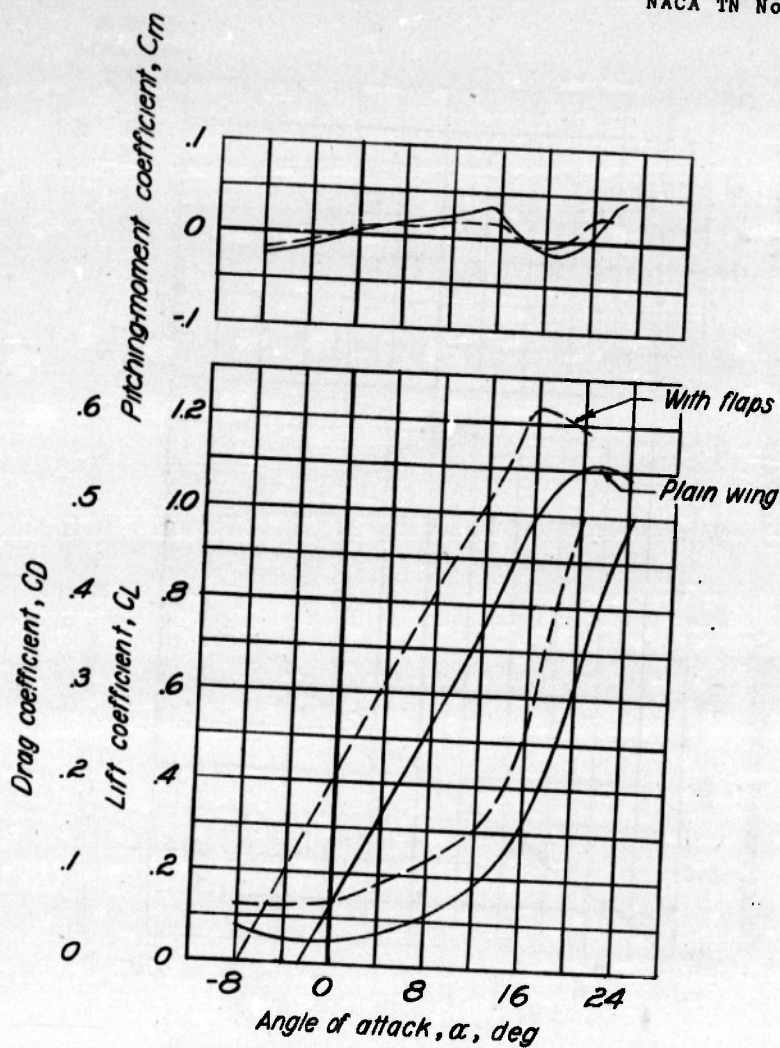
Figure 6.- Representative data from reference 2 showing the effect of a half-span split flap deflected 60° on the characteristics of a wing with an angle of sweepback of 45°.

27
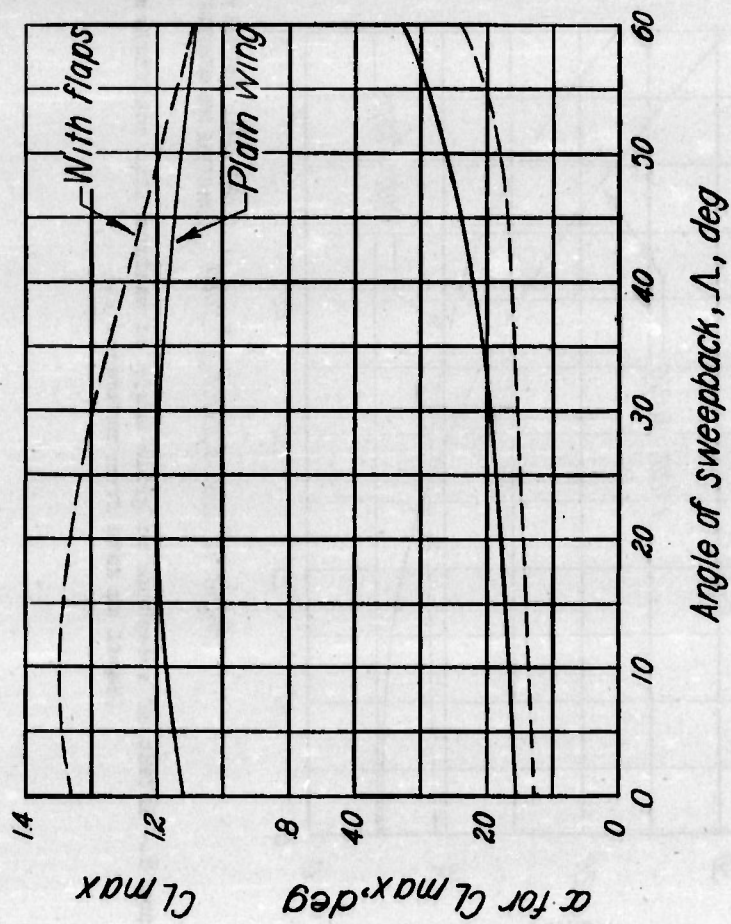
Figure 7.- Effect of sweepback on maximum lift characteristics. (Data from reference 2.)

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Fig. 8
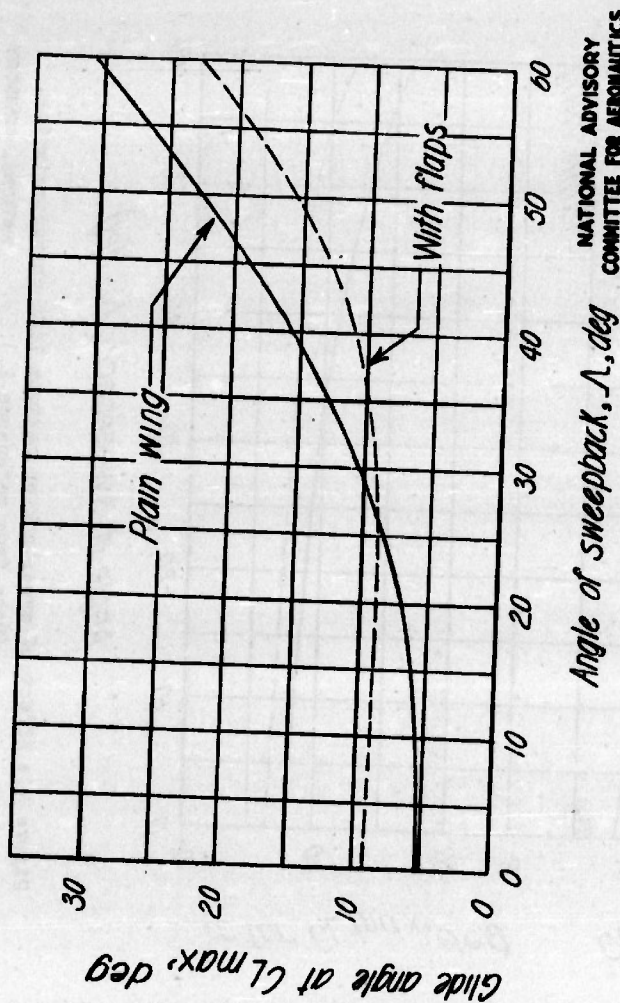
Figure 8.- Effect of sweepback on glide angle at maximum lift coefficient. (Based on data from reference 2.)
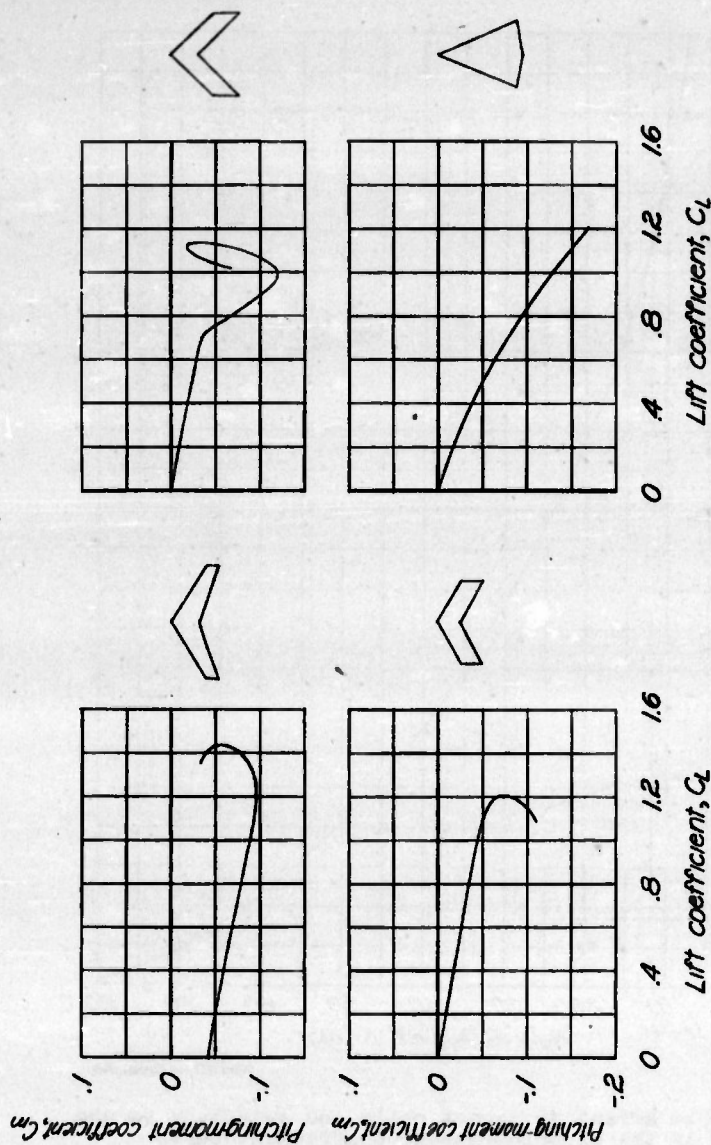
Fig. 10
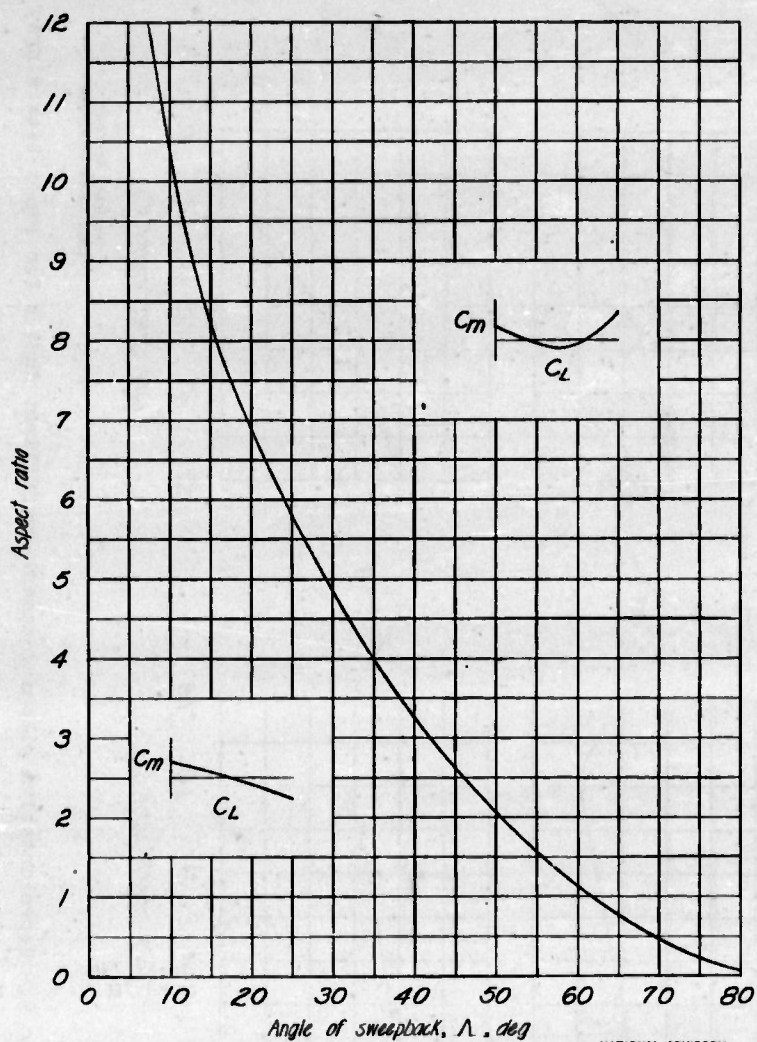
Figure 10.- Effect of aspect ratio and sweepback on the shape of the pitching-moment-coefficient curve.

Fig. 11
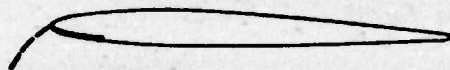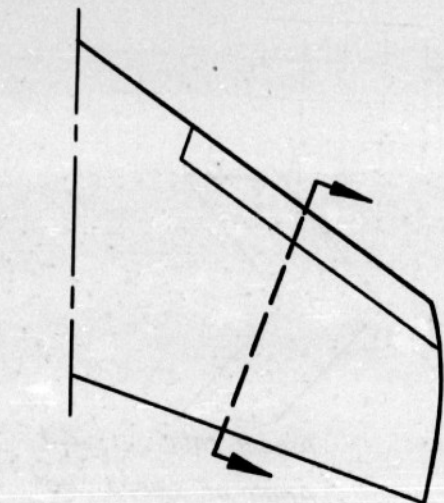
Nose flap
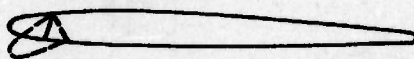
Drooped leading edge
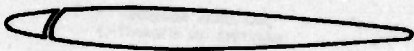
Slot

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Figure 11.- Leading-edge devices proposed for swept-back wings.

Fig. 12

NACA TN No. 1088
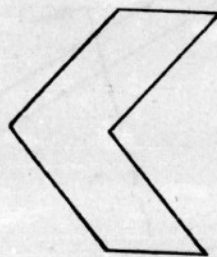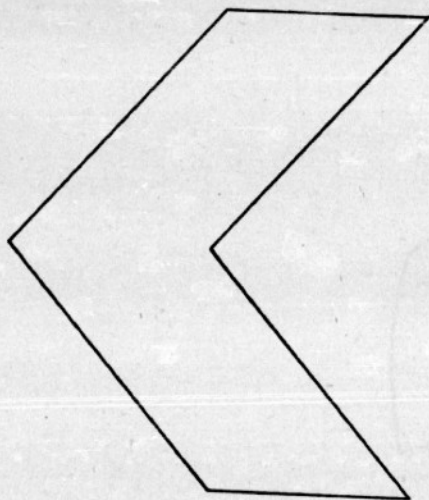
Aspect ratio   2.5

Angle of sweep   40°

$\dfrac{Area\ of\ tail}{Area\ of\ wing}$ 0.25

Wing and tail plan forms
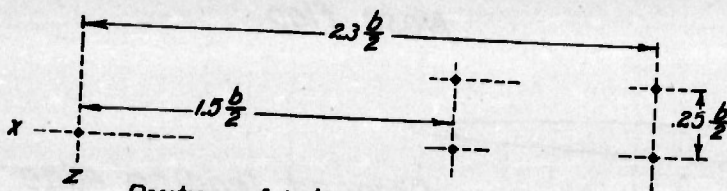
Positions of tail relative to wing M.A.C.

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Figure 12.- Configurations of model used in survey of
downwash behind swept-back wing.

33
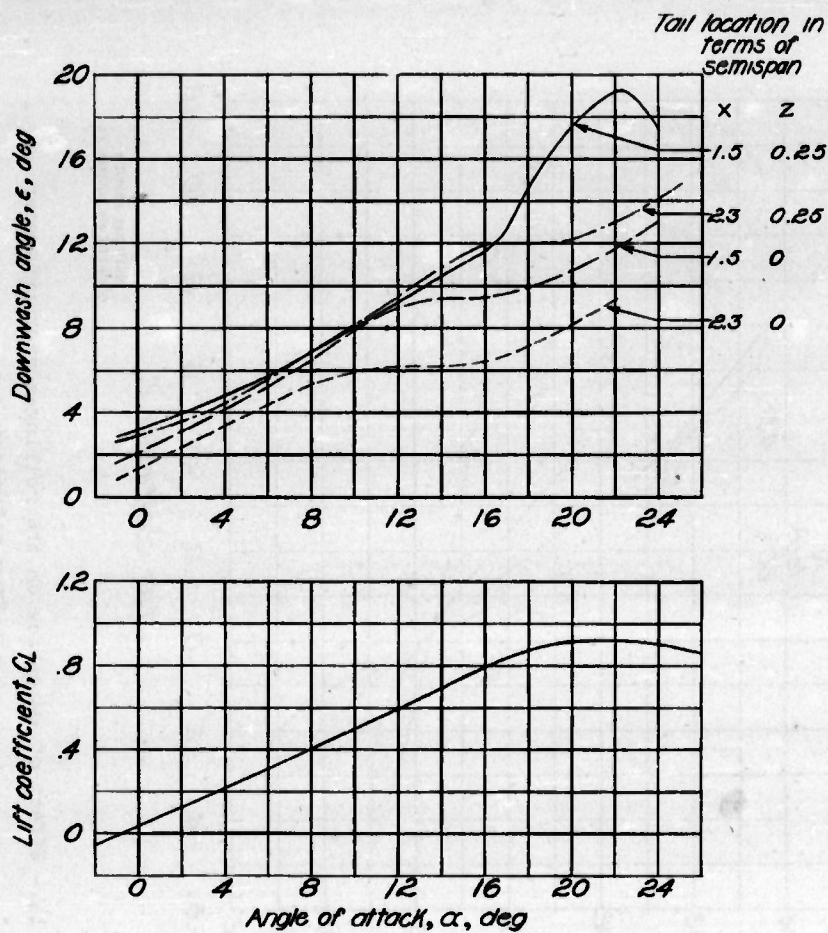
Figure 13.- Downwash angles behind swept-back wing at horizontal-tail positions given in figure 12.
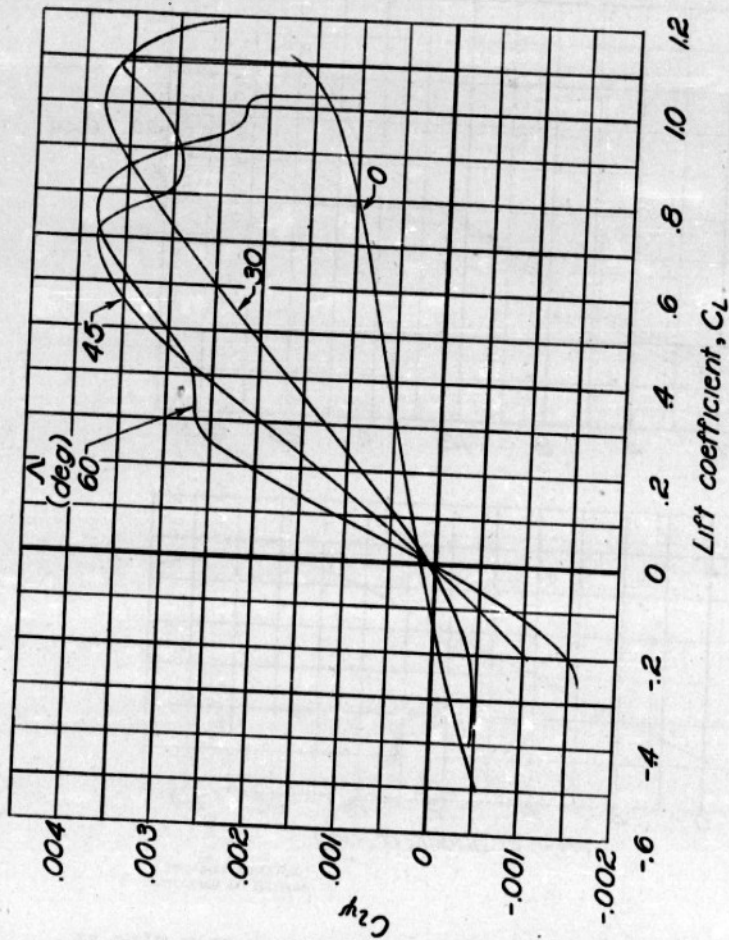
Figure 14.- Effect of sweepback on the rolling-moment parameter C_{l_ψ}.
(Data from reference 2.)

35
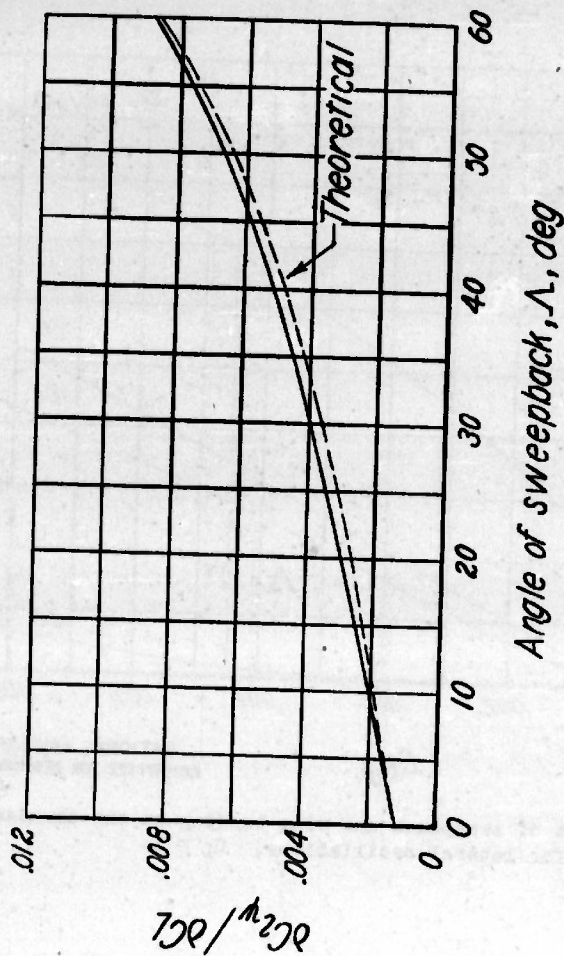
Figure 15.- Variation of the parameter $\partial c_{l_\psi}/\partial c_L$ with sweepback.
(Data from reference 2.)

Fig. 16   NACA TN No. 1088

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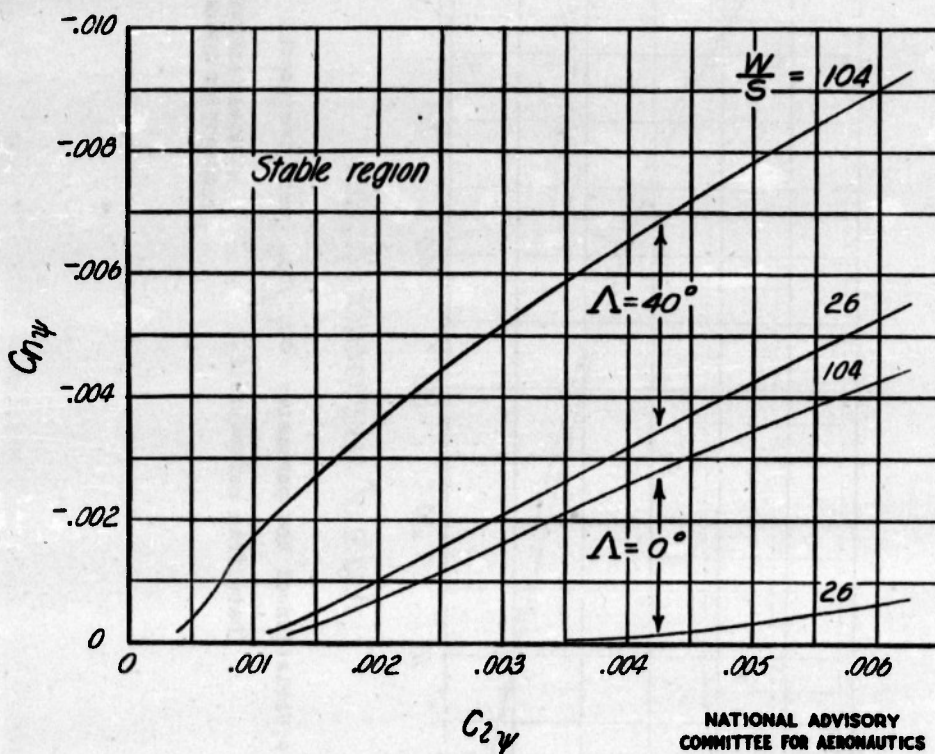
Figure 16.- Effect of sweepback and wing loading on the boundary
for lateral oscillations. $C_L = 1$.
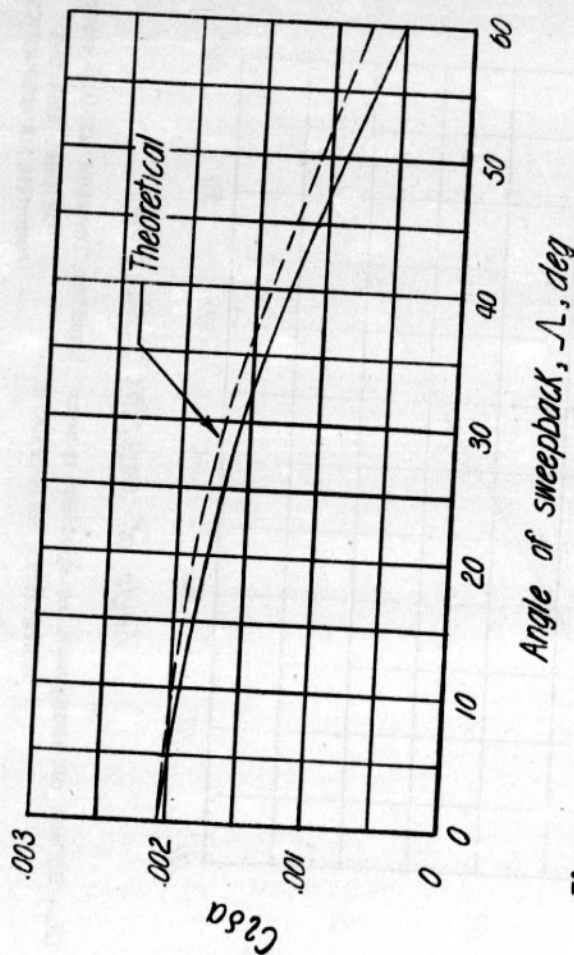
Figure 17.- Effect of sweepback on aileron power. $c_a = 0.2c$. (Data from reference 2.)
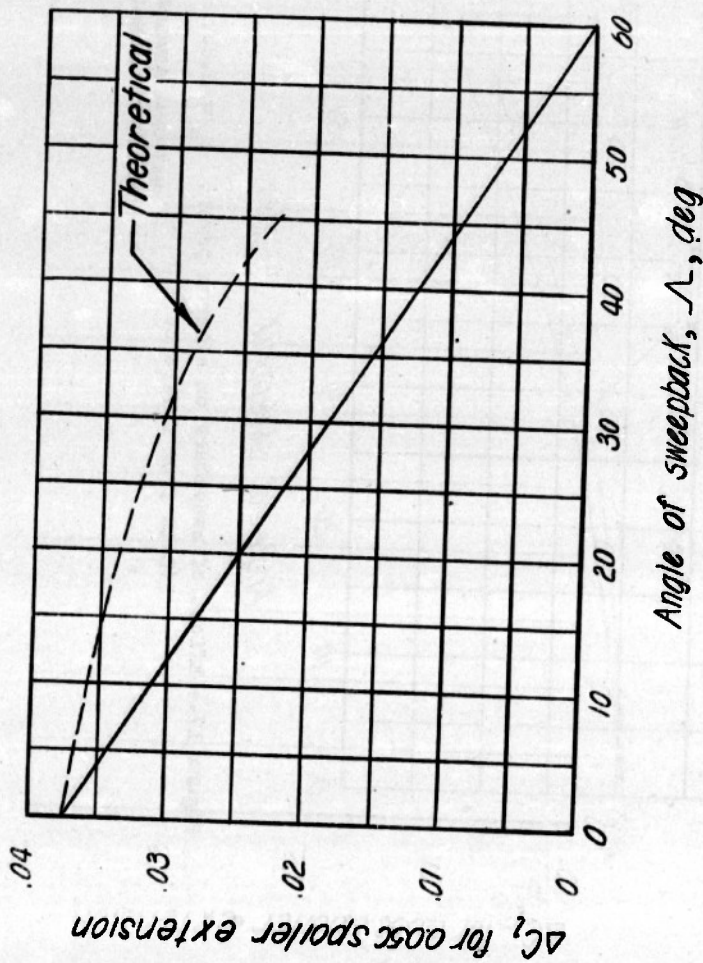
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Figure 18.- Effect of sweepback on spoiler power. Spoiler located at 0.8 chord. (Data from reference 2.)
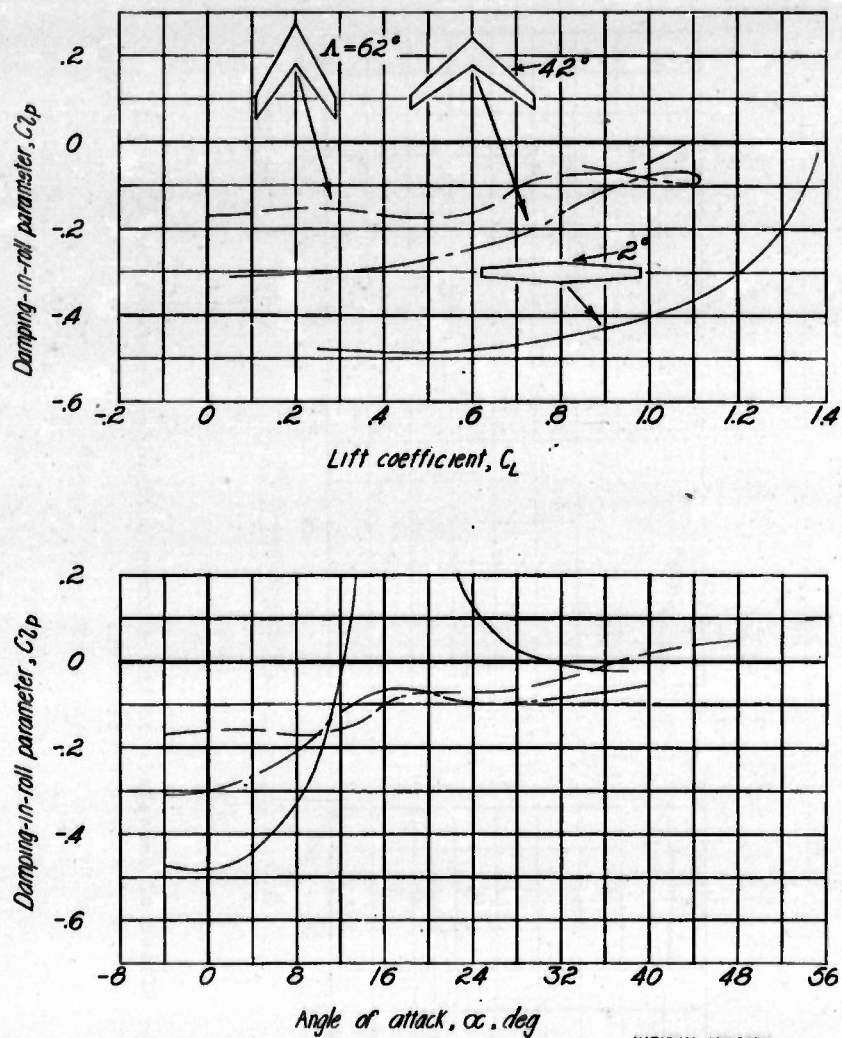
Figure 19.- Effect of sweepback on damping in roll.

Fig. 20
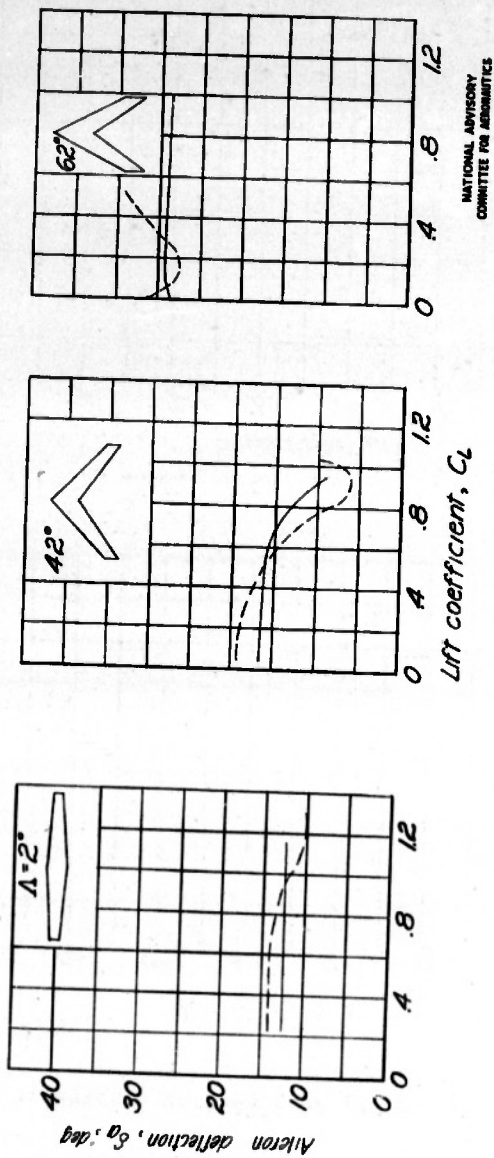
Figure 20.- Effect of sweepback on the aileron deflection required for $\frac{pb}{2V} = 0.1$.

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TITLE: Influence of Large Amounts of Wing Sweep on Stability and Control Problems of Aircraft

AUTHOR(S): Soule, H. A.
ORIGINATING AGENCY: National Advisory Committee for Aeronautics, Washington, D. C.
PUBLISHED BY: Same

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ABSTRACT:

Experience with swept-back wings and studies of them have indicated that the use of a large amount of sweep will, in itself, introduce stability and control problems of sufficient magnitude and complexity to require considerable research, particularly for flight at high angles of attack. This paper discusses these problems and, although no proved solutions are presented, in some cases promising lines for further investigation are indicated.

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